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Prediction of whole-body thermal sensation in the non-steady state based on skin temperature

Satoru Takada*, Sho Matsumoto, Takayuki Matsushita

Department of Architecture, Graduate School of Engineering, Kobe University, Rokkodaicho, Nada, Kobe 657-8501, Japan

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ABSTRACT

The goal of this study is to propose a new model for predicting thermal sensation in the non-steady state based on skin temperature and its time differential. A multiple regression equation for the prediction of the transient thermal sensation as a function of mean skin temperature and its time differential is determined based on the data obtained in subject experiments involving various non-steady state patterns during sedentary conditions. The results indicate a high correlation and a trend in good agreement between the predicted and experimental thermal sensations in a non-steady state, and showed that the proposed equation can predict transient whole-body thermal sensation with high precision. In addition, experiments incorporating processes with changes in metabolic rate (walking) were conducted on the subjects, and the applicability of the proposed equation, which was based on the data for sedentary conditions, to the conditions involving such a change in metabolic rate was studied. When the skin temperatures of all the body segments increase or decrease simultaneously, the predicted thermal sensation agrees well with the experimental results, allowing for the use of the proposed equation, while the application of the equation is more difficult for the cases in which skin temperature increases and decreases coexist over the segments of the body.

1. Introduction

The predicted mean vote (PMV) [1] has been widely used to predict thermal sensation in the steady state. The thermal sensation vote as a function of the thermal load (i.e., deviation from thermally neutral conditions) and the comfort equation are the essence of PMV and enable the prediction of thermal sensation based on thermal environmental elements, including air temperature, humidity, air velocity, thermal radiation, clothing, and metabolic rate, in a simple manner. However PMV cannot be adapted to predict thermal sensation in the non-steady state, necessitating the development of a method to predict thermal sensation in non-steady state.

The first step for the prediction of thermal sensation in the non-steady state is to obtain the thermal sensation vote in subject experiments. Gagge et al. [2] compared thermal sensation in a transient state with physiological responses and suggested that the change rate in skin temperature causes a sensation. Gagge et al. [3] referred to the prediction of thermal comfort in thermal equilibrium. Gonzalez et al. [4] showed experimental data on the sensation of warm discomfort under stepwise changes in ambient temperature, and the authors compared it with calculated SET* for the time series. Nevins et al. [5] showed experimental data on thermal sensation for thermal transients. Rohles et al. [6] showed the relationship between ET* and thermal sensation vote in the steady state. These studies discussed the relationship between psychological quantity (thermal sensation) and the physiological response or physical quantity of thermal environment and can be regarded as early attempts to predict thermal sensation in non-steady state. In these studies, the one-dimensional scale, which has two ends (hot and cold), was used to describe thermal sensation. Kuno et al. [7] pointed out the problems associated with using a one-dimensional scale for a transient state and proposed a two-dimensional description of thermal sensation, but it is not expressed in a quantitative form. Goto et al. [8] studied the time series of thermal sensation in the step-change in metabolic rate and proposed an equation related to thermal sensation. However, it is applicable only to a specific stepwise change and is not a general model for transient state.

The prediction of thermal sensation for a given thermal environmental condition can be divided into two processes as shown in Fig. 1. The first is the prediction of thermophysiological responses (e.g., skin and core temperatures) based on the given

* Corresponding author. Tel./fax: +81 78 803 6038.
E-mail address: satoruta@kobe-u.ac.jp (S. Takada).

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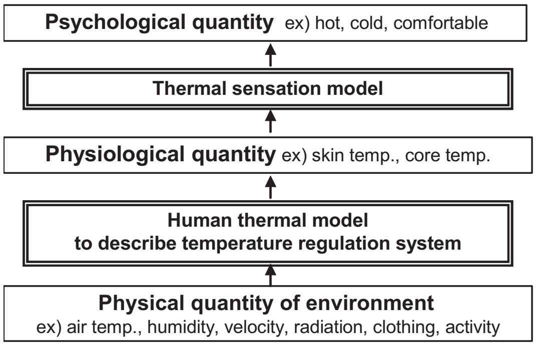

Fig. 1. Schematics for the prediction of psychological responses under the given environmental conditions.

environmental physical conditions (e.g., air temperature, humidity, air velocity, and radiant temperature), and the second is the prediction of psychological responses (e.g., hot, cold, or comfortable) based on thermophysiological responses. For PMV, as an index for steady state, the two procedures are not divided, and the predicted thermal sensation in the steady state can be calculated directly from the given thermal environmental conditions. However, for non-steady state, because the number of the state to be handled is far greater, it might be more convenient to divide the processes into two parts. When real-time thermophysiological responses are available based on measurements, we need only to build a model to predict thermal sensation from thermophysiological responses. If the real-time physiological responses are not available as measured data, it is possible to obtain them from the human thermal model, though the error in this model [9,10] will be mixed in the prediction of the thermal sensation.

Several models for predicting transient thermal sensation based on thermophysiological responses have been proposed with this point of view in mind. Mori et al. [11] presented a regression equation for thermal sensation based on physiological variables (mean skin temperature and its time differential, tympanum temperature and its time differential, and heat flux at the skin's surface). Fiala et al. [12] proposed a similar equation based on the mean skin temperature and its time differential and core temperature. Recently, Zhang et al. [13–15] proposed a model for predicting not only whole-body thermal sensation but also local thermal sensation in the non-steady state by using the mean and local skin temperatures, their time differential, and the time differential of the core temperature. However, the necessity of considering the core temperature or its time differential as an explanatory variable for the transient thermal sensation is not clearly indicated in these studies. Frank et al. [16] experimentally studied the contribution of core and skin temperatures to thermal comfort, and showed that core and skin temperatures contribute approximately equally to thermal comfort. However this was a physiological experiment conducted by cooling the core using a neurotransmitter, which varies from the ordinal conditions experienced in daily life. Meanwhile, using water bath experiments, Mower [17] showed that thermal sensation is independent of the core temperature. In contrast, there is clear evidence that skin temperature and its change rate are the input to thermoreceptors, which suggests that they should closely relate to thermal sensation. Hensel [18] has used neurophysiological experiments to show that the general properties of cutaneous thermoreceptors have a static response (dependent on skin temperature) and a dynamic response (dependent on skin temperature changes). Based on this study, Ring et al. [19,20] developed a model to describe the dynamic response of cutaneous thermoreceptors to temperature stimuli based on the heat conduction equation for skin. Ring et al. [19] showed that the relationship between the thermal sensation and the dynamic responses of cutaneous thermoreceptors are linear.

It would be impossible to completely neglect the influence of core temperature on thermal sensation. However, it is true that the evidence supporting its influence is weaker than that of skin temperature. Moreover, as a realistic problem to predict thermal sensation based on the body temperature, it is not convenient to consider core temperature because the range of variation in core temperature is in general significantly smaller than that of skin temperature [21], and because variation in core temperature among individuals is not small [22]. Skin temperature is significantly easier to measure than core temperature, and its change is more dynamic. If the intrinsic information used to predict transient thermal sensation is confined to skin temperature and its time differential, the prediction is significantly reduced in complexity in comparison to that considering both skin and core temperatures.

This study attempts to build and validate an equation that explains whole-body thermal sensation in the non-steady state based only on mean skin temperature and its time differential. This approach relies on nonlinear regression and uses the data obtained in the following three types of the experiments.

- Experiment 1 (described in Section 2): this is the basic experiment used to build the equation, and is conducted in a thermally homogeneous environment, which is realized in artificial climate chambers. Sedentary subjects are used, exposed to thermally transient conditions (a stepwise change in air temperature). By using the data, the regression analysis is performed and the equation is developed.
- Experiments 2 & 3 (described in Section 3): these experiments are used to validate the proposed equation, and simultaneously, to identify the applicable range of the equation. Experiment 2 is conducted under the situation of ordinary indoor and outdoor spaces (in a university campus), including exposure to a thermally inhomogeneous environment, as well as walking processes. Based on Experiment 2, the validity of the proposed equation is shown. In Experiment 3, the walking process in the thermally homogeneous environment is focused on. In this situation, the skin temperature of some parts of the

Table 1
Air temperature settings for Experiment 1 (conducted in an artificial climate chamber).

Schedule	Time[min] (0–200)				
1	29°C	35°C	26°C		
2	29°C	20°C	29°C	38°C	29°C
3	29°C	20°C	29°C	38°C	29°C
4	29°C	20°C	29°C	38°C (70%RH)	29°C
5	29°C	20°C	29°C	38°C (70%RH)	29°C

70%RH * Other processes are 50%RH

body increases, while that of the others decreases. The applicable limit of the proposed equation is shown through this experiment.

2. Proposal of an equation for predicting thermal sensation in the non-steady state

2.1. Concept of the proposed equation

The equation for predicting thermal sensation as a function of mean skin temperature and its time differential is created by performing a nonlinear multiple regression analysis. Based on an experimental dataset of the thermal sensation vote and mean skin temperature in various non-steady states, a regression equation of the thermal sensation vote with two explanatory variables (the normalized mean skin temperature $T_{sk,n}$ and its time differential $dT_{sk,n}/dt$) is determined as in Eq. (1):

$$\mathrm{TSV} = a_1 + a_2\left[\frac{1}{2} + \frac{a\tan\left(\frac{T_{sk,n}-a_3}{a_4}\right)}{\pi}\right] + a_5\left[\frac{1}{2} + \frac{a\tan\left(\frac{\frac{dT_{sk,n}}{dt}-a_6}{a_7}\right)}{\pi}\right] \quad (1)$$

In Eq. (1), a_1–a_7 are the regression coefficients determined by the regression analysis. This function indicates that the predicted value of the thermal sensation (TSV) increases (i.e., shifts to the hotter side) as either the skin temperature $T_{sk,n}$ or the time differential of the skin temperature $dT_{sk,n}/dt$ increases. To compensate for inter/intra individual differences in skin temperature, the mean skin temperatures were normalized based on the mean skin temperature in the thermally neutral and steady state for each experiment ($T_{sk,0}$), as shown in Eq. (2):

$$T_{sk,n}(t) = T_{sk}(t) - T_{sk,0} \quad (2)$$

where $T_{sk,n}$ and T_{sk} are the functions of time, and $T_{sk,0}$ is a constant for a series of experiments. Here, it is assumed that the time

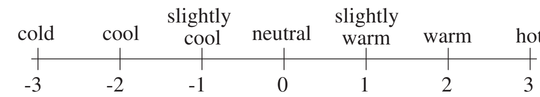

Fig. 2. Thermal sensation scale.

differential of the mean skin temperature does not include inter/intra individual differences, that is,

$$dT_{sk,n}/dt = dT_{sk}/dt \quad (3)$$

2.2. Subject experiments (Experiment 1)

The subject experiments for thermally transient exposure (hereafter called Experiment 1) were conducted on 15 subjects (all male, ranging from 22 to 30 years in age). The subjects were student volunteers, and in good health. Five cases involving a change in room air temperature (Table 1) were provided to encompass changes in typical everyday life. In the time series of these five cases, various transient situations were included. The 15 subjects attended these five cases as shown in Table 2, and 43 series of experiments were conducted in total. Two artificial climate chambers (with a control precision of temperature ±0.5 °C, and relative humidity ±3%) were used to simulate a thermally homogeneous environment. In all experiments, the subjects maintained a sedentary position and wore only trunks (0.03 clo). Skin temperatures were measured based on the 7-point method presented by Hardy and DuBois [23], by using thermocouples (T-type, 0.2 mm in diameter). The data were recorded at 10-s intervals using a data logger (CADAC 21, Eto Denki Co., with a precision of ±0.2 °C for temperature measurement by T-type thermocouple). The thermal sensation votes were recorded on paper by one of the individuals conducting the experiment at 1-min intervals. The ASHRAE 7-point scale (Fig. 2) was used for the thermal sensation votes. Before the start of each experiment, the subject remained sedentary under the first environmental condition (room air temperature controlled to 29 °C) for more than 30 min.

2.3. Detailed method of determining the equation

As shown in Tables 1 and 2, the total experimental time was 6140 min over the course of a series of 43 experiments. The time interval for recording the thermal sensation vote was 1 min; thus, 6140 datasets should be obtained. It should be noted that several

Table 2
Information on and experimental schedule for each subject (Experiment 1).

Subject	Age [year]	Height [cm]	Weight [kg]	Body surface area [m^2]	Sex	Attendance [times] Schedule				
						1	2	3	4	5
A	24	169	58.8	1.67	Male	4	2	2		
B	24	167	64.4	1.71	Male	4	2	1		
C	23	162	56.7	1.59	Male	4	2	1		
D	24	173	72.1	1.83	Male	3	1	1		
E	30	170	76.8	1.85	Male			1		
F	23	174	74.5	1.86	Male			1		
G	23	170	84.4	1.91	Male			1	1	1
H	23	178	79.0	1.94	Male			1		
I	22	170	56.4	1.65	Male			1	1	1
J	22	162	56.4	1.59	Male			1		
K	22	173	56.7	1.68	Male				1	1
L	23	164	47.1	1.50	Male					1
M	25	177	93.6	2.05	Male					1
N	22	170	59.9	1.69	Male					1
O	23	171	61.6	1.71	Male					1

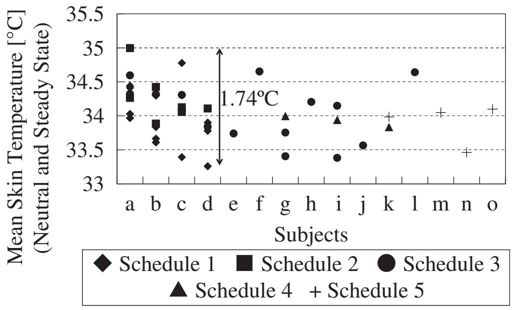

Fig. 3. Mean skin temperatures for each experiment in the neutral and steady states.

datasets were lost, giving 6082 available datasets. By using the available datasets on mean skin temperature, its time differential, and the thermal sensation vote, the regression coefficients included in Eq. (1) were determined to best fit the data (nonlinear multiple regression). The time differential of skin temperature was determined by analytically differentiating the continuous function fitted to the time series of the skin temperature data.

The data satisfying the following two inequalities are categorized as the data in the thermally neutral and steady states, or $|TSV| \leq 0.5$ and $|dT_{sk}/dt| \leq 0.05$, respectively. $T_{sk,0}$ was determined by averaging these data for each series of experiments.

2.4. Results

Fig. 3 shows the mean skin temperatures in the thermally neutral and steady states for each experiment. The inter/intra individual differences in skin temperature are nearly 2 °C at maximum.

Table 3 shows the resulting regression coefficients (a_1–a_7), while the correlation between the experimental and predicted values of the thermal sensation vote (TSV) is shown in Fig. 4. From the correlation coefficient (0.873), the experimental values and predicted values are in good agreement. The presentation of the regression equation is shown in Fig. 5. The TSV becomes higher as the $T_{sk,n}$ or $dT_{sk,n}/dt$ value is higher. The TSV changes significantly near $T_{sk,n} = 0$ and $dT_{sk,n}/dt = 0$.

Figs. 6–11 show several examples of the time series associated with the experiment that forms the regression data. Each figure consists of two graphs: graph (a) shows the skin temperature and its time differential, which were used to calculate the TSV. The mean skin temperatures in the thermally neutral and steady states for each experiment ($T_{sk,0}$) are also shown in this graph. Graph (b) shows a comparison between the experimental and calculated TSV. The results calculated by the other models (the linear regression model and the nonlinear model without the normalization of skin temperature) are also depicted in the figures and explained in the discussion (refer to "cal_NN" in the figures in this section).

As shown in the figures, the predicted trend in the TSV (nonlinear equation using normalized skin temperature) agrees well with the experimental values. In particular, the trends of the experimental values of TSV immediately following the ambient temperature change are well reproduced in the calculated values.

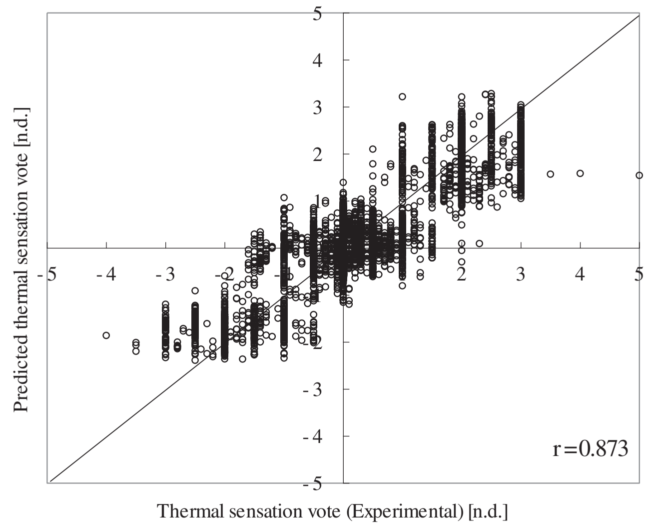

Fig. 4. Comparison of the experimental and predicted thermal sensation vote values.

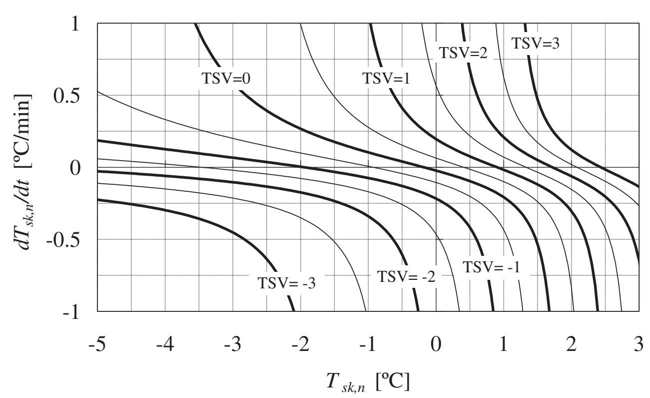

Fig. 5. Presentation of the equation for predicting thermal sensation in the non-steady state based on skin temperature ($T_{sk,n}$ is the normalized mean skin temperature and $dT_{sk,n}/dt$ is its time differential).

For example, as shown in Figs. 6–11, at minute 30, the air ambient temperature is decreased from 29 °C to 20 °C stepwise, and both the experimental and calculated values of TSV suddenly changed to "cool" or "cold" in the same manner. This is true of the other ambient temperature change situations as well. In some parts, the experimental and calculated values disagree; however the differences between the values are almost within 1 in TSV (for example, the calculated result is "warm"(+2) while the experimental result is "hot" (+3)). This difference is not highly significant, and in most cases, the direction of thermal sensation (hot side or cold side) is well predicted. Additionally, for the time series that were not described in these figures, the predicted and experimental trends in the TSV show good agreement. Thus, the results suggest that the proposed equation successfully predicts thermal sensation in the non-steady state during sedentary conditions.

Table 3
Regression coefficients and correlation coefficient ("NN" or nonlinear equation with normalization of skin temperature).

Regression coefficient							Correlation coefficient	Number of data
a_1	a_2	a_3	a_4	a_5	a_6	a_7		
11.018	−12.511	2.430	−2.791	−3.969	−0.035	−0.203	0.873	6082

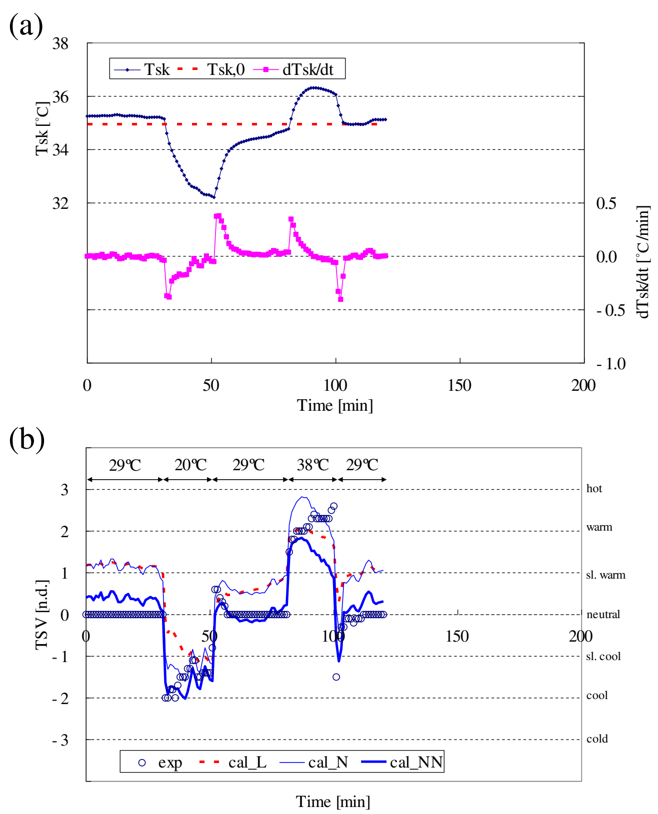

Fig. 6. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject A, Schedule 2 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature).

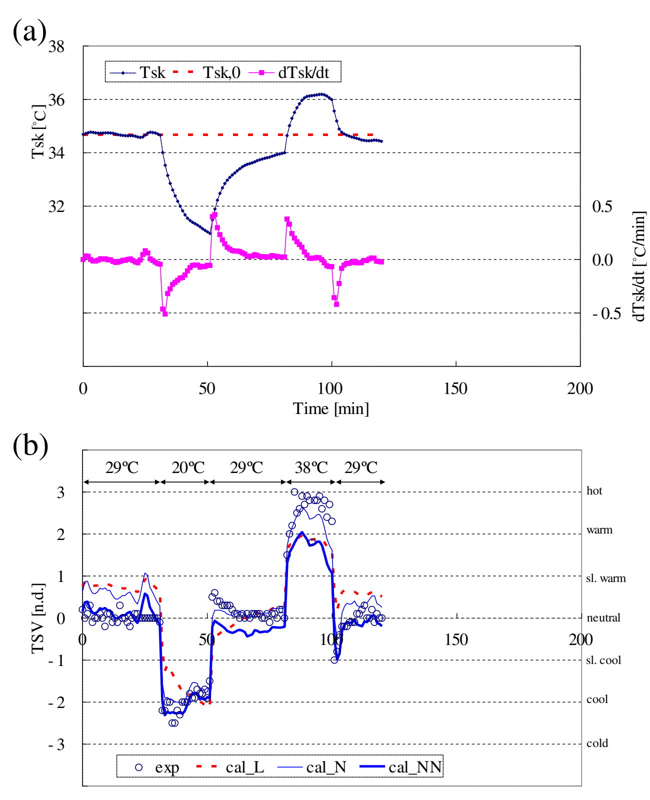

Fig. 7. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject B, Schedule 2 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature).

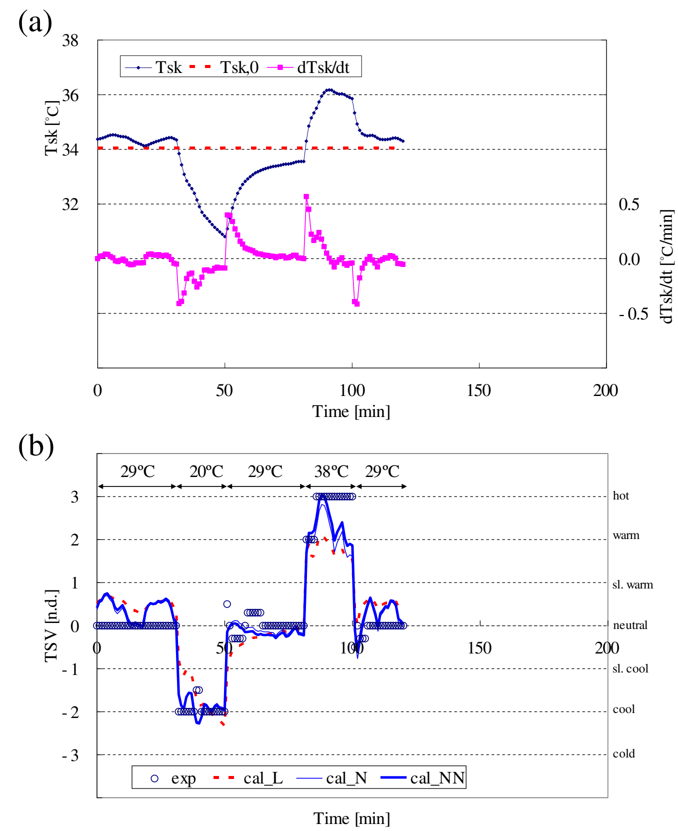

Fig. 8. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject C, Schedule 2 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature).

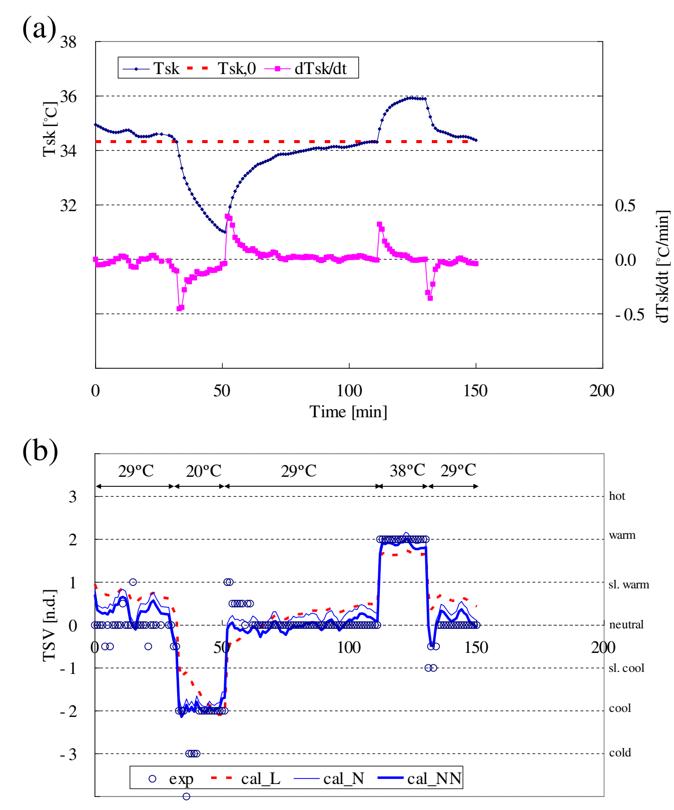

Fig. 9. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject B, Schedule 3 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature).

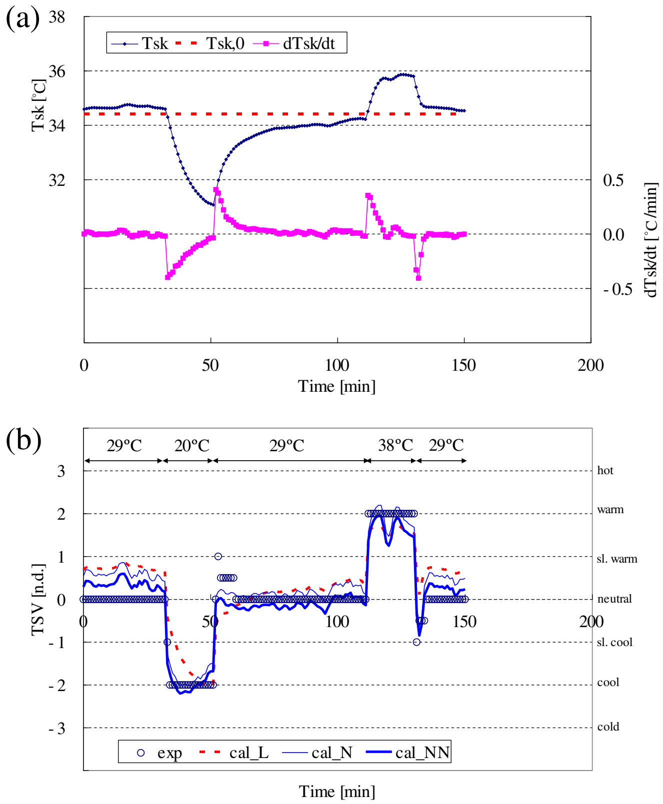

Fig. 10. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject C, Schedule 3 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature).

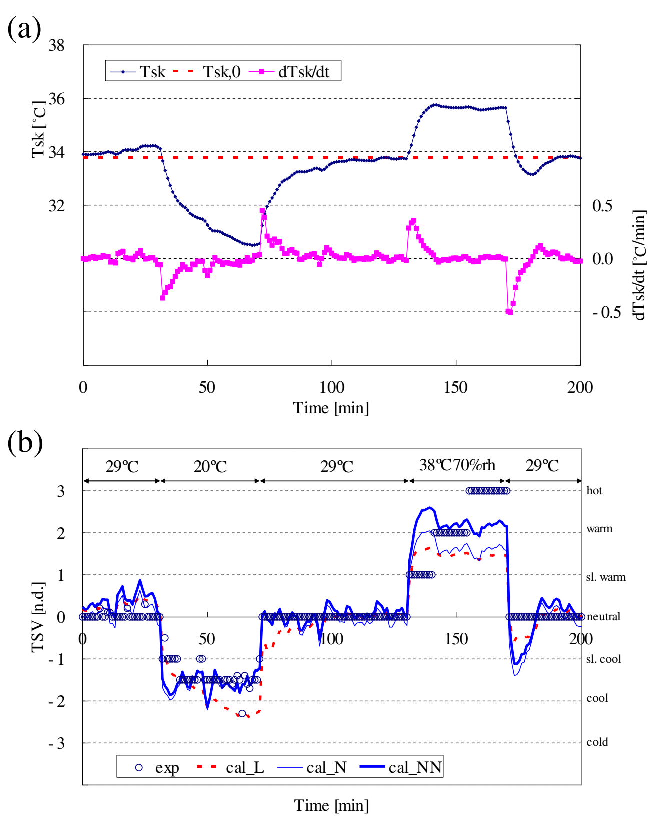

Fig. 11. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject G, Schedule 5 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature).

Table 4
Physical characteristics of subjects (Experiments 2 and 3).

Subject	Age [year]	Height [cm]	Weight [kg]	Body surface area [m^2]	Sex	Clothing [clo]
P	23	171	64.0	1.74	Male	0.5
Q	22	177	61.0	1.76	Male	0.5

3. Validation of the proposed equation

3.1. Method (Experiments 2 and 3)

The proposed equation for predicting the TSV in the non-steady state was derived from the experiments performed on sedentary subjects in the thermally homogeneous environment realized in artificial climate chambers. In this section, the applicability of the proposed equation to conditions other than the sedentary condition in the thermally homogeneous environment is checked.

Two types of subject experiments (Experiments 2 and 3) were conducted in the field, as a more realistic situation with respect to everyday life. Experiment 2 includes walking processes with a change in the ambient temperature, and Experiment 3 includes walking processes at a constant temperature. Two subjects (Subjects P and Q in Table 4) were involved in Experiments 2 and 3. These subjects were male student volunteers in good health, and wore an ordinary summer clothing outfit 0.5 [clo] as shown in Table 4. In Experiment 2, the subjects move between an air-conditioned room and a non-air-conditioned space (a non-air-conditioned room and an outdoor space in summer season) on a university campus, as shown in Table 5. Although the subjects wore sensors on their skin surface, the situation during Experiment 2 is similar to that of the ordinary campus life of students. In Experiment 3, the subjects repeated two sets of walking and resting sequences (Table 6) in a basement floor corridor where the air temperature was almost constant and the influences of air movement and solar radiation were minimal. Before starting either experiment, the subjects waited for 30 min in a thermally neutral condition. Their thermal sensation votes and skin temperatures were measured in the same way as in Experiment 1, although the temperatures were measured using a different instrument. In Experiments 2 and 3, the skin temperatures were measured using a thermistor with a battery-powered data logger (LT-8, Gram Corporation, with a resolution of 0.01 °C).

3.2. Results

3.2.1. Experiment 2: walking and resting with a change in ambient condition

Figs. 12 and 13 show the time series associated with Experiment 2, which considers walking processes with a change in ambient temperature. The mean skin temperatures in the thermally neutral state were 34.5 °C (Subject P) and 34.9 °C (Subject Q). When the subjects were walking in an outdoor space (minutes 110–130), the TSV showed dynamic variation in a short cycle, under a dynamic change in solar radiation and wind velocity, and the trend of the calculated TSV follows the experimental TSV well for both subjects (Figs. 12(b) and 13(b)). However, for the second walking process (minutes 210–230), the agreement between the calculated and experimental TSVs is not as good as that of the first walking process. As shown in Figs. 12(c) and 13(c), the local skin temperatures varied almost simultaneously in the first walking process (minutes 110–130); however, for the second interval (minutes 210–230), the skin temperatures at the thigh, legs, and feet increased while those at the other segments decreased. The

Table 5
Time schedule for Experiment 2.

Time[min]	0–30	30–50	50–70	70–90	90–110	110–130	130–150	150–170	170–190	190–210	210–230	230–250	250–270	270–300
Location	A	N	A	N	A	O	A			O			A	
Action	PC	S				W	M	S	PC	S	W	S		PC
Temperature [ºC]	27	31	23	31	26	32	27	27	27	33			27	
Insolation	×	×	×	×	×	○	×	×	×	×	○	×	×	

Location A : Air-conditioned room
N : Non air-conditioned room
O : Outdoor

Action PC : Computer Working
S : Sedentary
W : Walking (=3.0METs**)
M : Meal

** Measured by 3-dimensional accelerometer (Panasonic EK4800-K)

Metabolic rate [W/m^2]= x [METs]•1.18 •Weight[kg]/Body surface area [m^2]

Table 6
Time schedule for Experiment 3.

Time[min]	0–20	20–40	40–60	60–80	80–100
Action	Sedentary	Walking (3.0METs)	Sedentary	Walking (4.0METs)	Sedentary
Environment	Temperature : 26.2～26.7ºC, Relative Humidity : 65～75%				

difference between the two processes lies in the environment experienced immediately prior to starting the walk: the first walking process followed a sedentary stay in an air-conditioned room (minutes 90–110), while the second followed a stay in non-air-conditioned room. Hence the change in the skin temperature was more abrupt in the first process. Even though the errors accompanying the field measurement should be contained greater than in Experiment 1, the agreement between the predicted and experimental tendency of the thermal sensation votes is fairly good as an overall transient process. Experiment 2 supports the validity of the proposed equation.

3.2.2. Experiment 3: walking and resting in a constant ambient condition

Figs. 14 and 15 show the time series associated with Experiment 3, which considers walking processes in an approximately constant-temperature condition. Figs. 14(b) and 15(b) show the experimental and predicted values of thermal sensation votes over different trends for Subjects P and Q. The subjects' mean skin temperatures in the thermally neutral state were 33.9 °C (Subject P) and 35.2 °C (Subject Q). While walking, the predicted TSV values decrease because of the decrease in mean skin temperature, while the experimental TSV increases especially in the latter half of the walking processes.

One of the reasons for the discrepancy in the thermal sensation tendencies may lie in the method used to measure the mean skin temperature. Hardy and DuBois's 7-point method (head, abdomen, forearm, hand, thigh, leg, and foot) is significantly affected by the skin temperature of the abdomen, which is used as the representative of the trunk segment because of its significant weight. However, the influence of the heat produced predominantly in the muscles of the thigh and leg segments conflicts with that of the cooling provided by the airflow due to walking, as shown in Figs. 14(c) and 15(c). The skin temperature values at the thigh, legs, and feet increase, while those of the other segments decrease. The influence of skin temperature on such regions may not be properly reflected in the mean skin temperature, although the influence of signals from the skin at such regions would be significant with respect to thermal sensation.

4. Discussion

4.1. The necessity of normalizing skin temperature

In the equation proposed for predicting the TSV in the non-steady state, the mean skin temperatures are normalized based on the mean skin temperatures in the thermally neutral state to compensate for inter/intra individual differences. An equation without this normalization was applied in the same way by using Eq. (1) as follows:

$$\mathrm{TSV} = a_1 + a_2\left[\frac{1}{2}+\frac{a\tan\left(\frac{T_{sk}-a_3}{a_4}\right)}{\pi}\right] + a_5\left[\frac{1}{2}+\frac{a\tan\left(\frac{\frac{dT_{sk}}{dt}-a_6}{a_7}\right)}{\pi}\right] \tag{4}$$

where $T_{sk,n}$ is replaced by T_{sk} in Eq. (4). The resulting coefficients of Eq. (4) are shown in Table 7, and the regression coefficient is 0.839. The prediction made by the equation based on non-normalized skin temperature is adequate as shown in Figs. 6–11 (see "cal_N" in the figures). Without normalization, the predicted TSV was too high/low for some of the data series in which the skin temperature as a whole is higher/lower than the average (for example, in Figs. 6 and 7, the skin temperature tends to be higher in these subjects). For such data series, the calculated results are improved by normalizing the skin temperature (i.e., adjusting the baseline). This difference causes the regression coefficient for the normalized equation to be better than that of the non-normalized equation.

4.2. Equation type used for prediction

In this paper, the nonlinear type equation (additive of Lorentzian cumulative functions such as Eq. (1)) was adopted for the

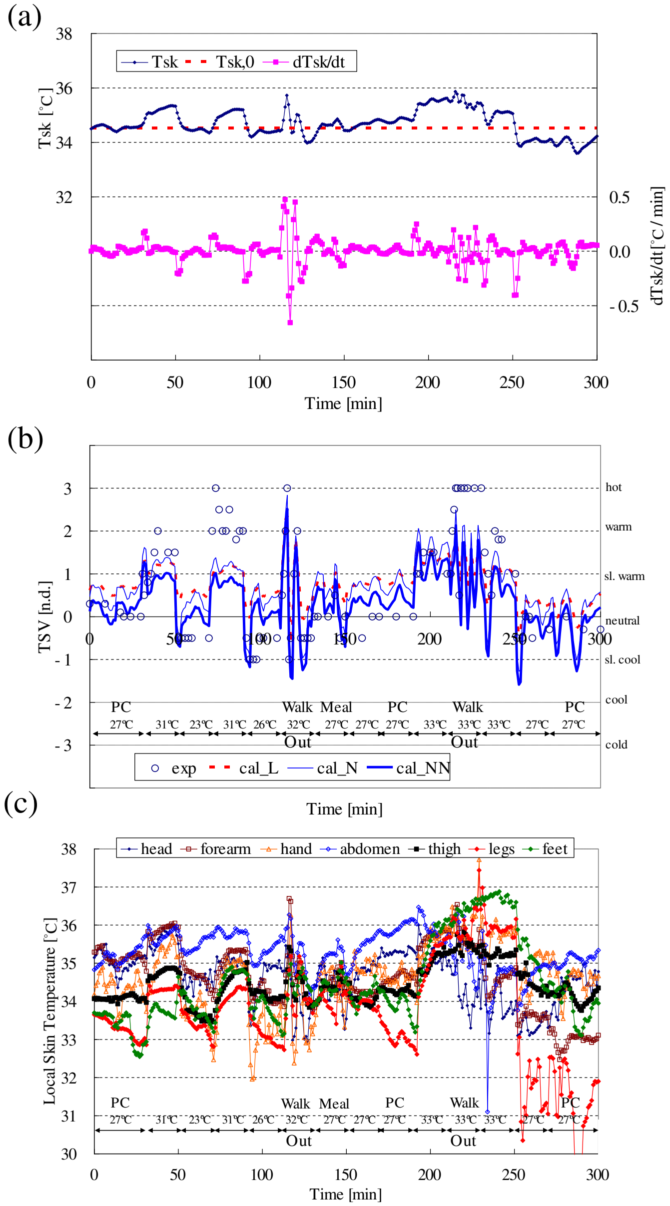

Fig. 12. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject P, Experiment 2 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature), and (c) local skin temperatures (experimental).

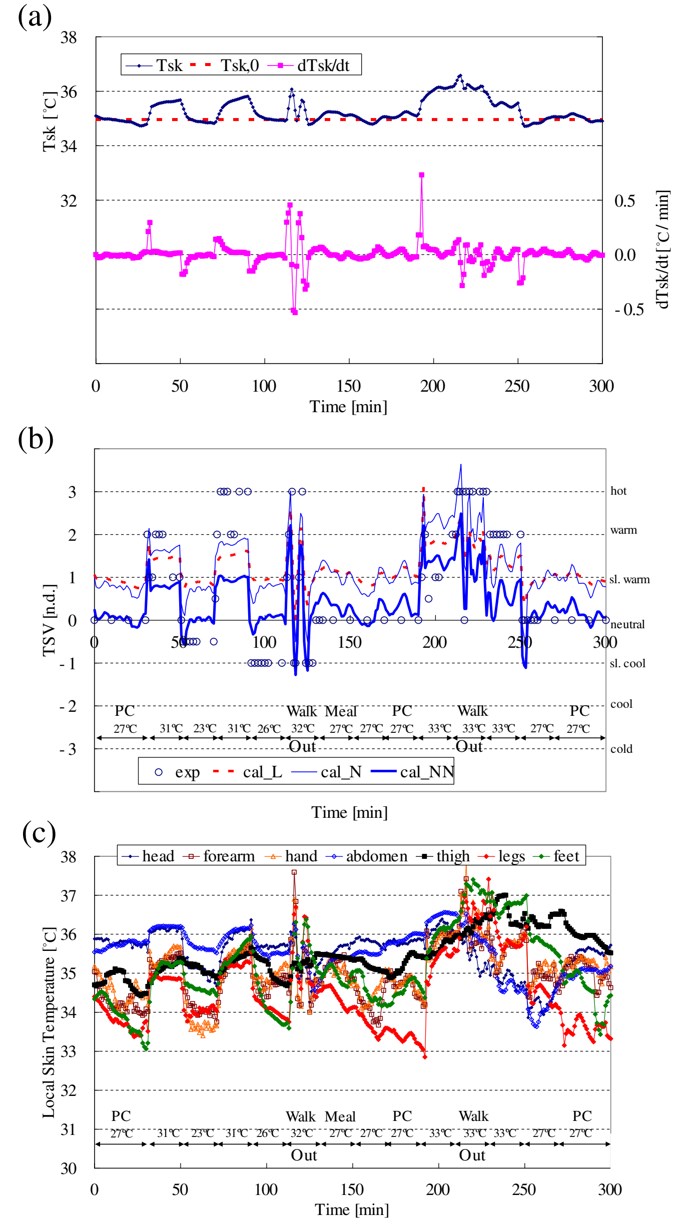

Fig. 13. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject Q, Experiment 2 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature), and (c) local skin temperatures (experimental).

regression of the TSV using the skin temperature and its time differential. This function was selected from a significant number of various continuous polynomials because it best fits the experimental data. The candidate functions are the polynomials provided by software for function fitting (Table curve 3D, SYSTAT Software Inc.); additionally the software optimized the type of function used.

As the simplest equation form, a linear regression including all of the variables was also attempted, based on Eq. (5):

$$\mathrm{TSV} = a_1 + a_2 T_{sk} + a_3 \frac{dT_{sk}}{dt} \tag{5}$$

The resulting coefficients of Eq. (5) are shown in Table 8, and the regression coefficient is 0.799. Prediction by the linear equation was not unfavorable, as shown in Figs. 6–11; however, the sharp changes in TSV due to the stepwise change in air temperature are not described well by this equation. The nonlinear equations have an advantage in that regard. At the same time, it could be said that the consideration of T_{sk} and dT_{sk}/dt explains the TSV in the non-steady state to some degree, even with a linear equation. The linear equation is sufficient, at least for the scenario approximating the steady state.

4.3. Prediction for the steady state

The proposed equation applies to the non-steady state. The steady state is a special case of the non-steady state; by setting $dT_{sk,n}/dt = 0$, the proposed equation can be used for this steady state, meaning that the steady state thermal sensation can be predicted by skin temperature alone. Ogawa et al. [24] conducted subject experiments and showed that the thermal sensation in the

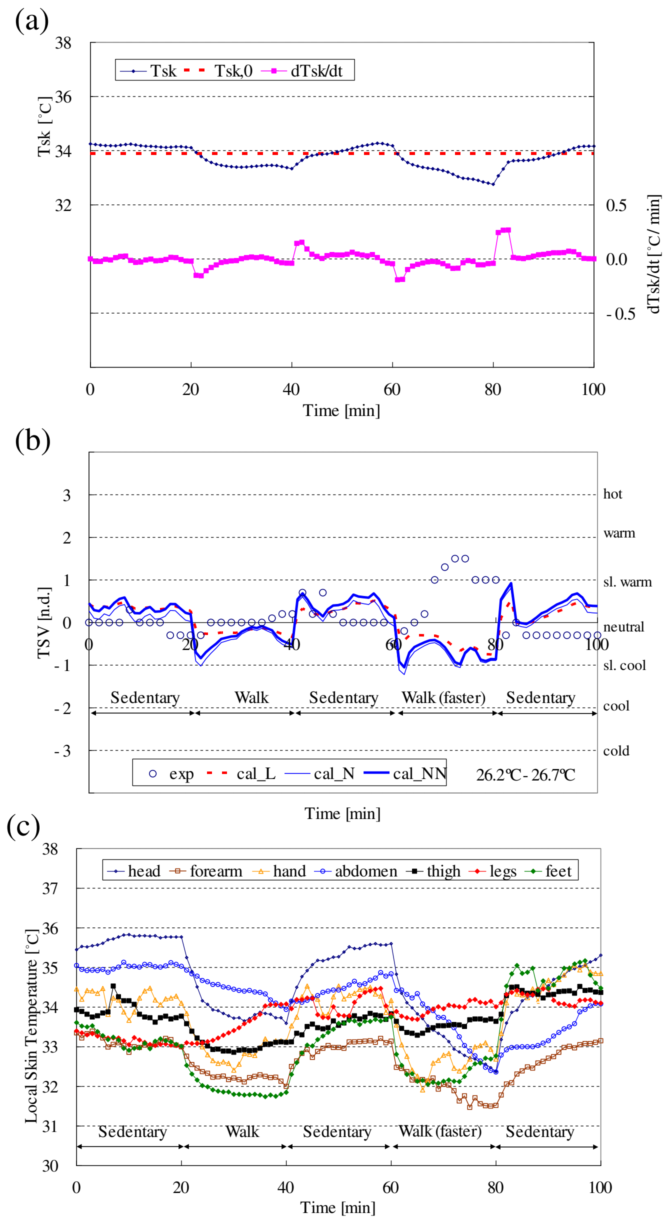

Fig. 14. (a) Mean skin temperature and its time differential (experimental), (b) thermal sensation vote (experimental and calculated) for Subject P, Experiment 3 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature), and (c) local skin temperatures (experimental).

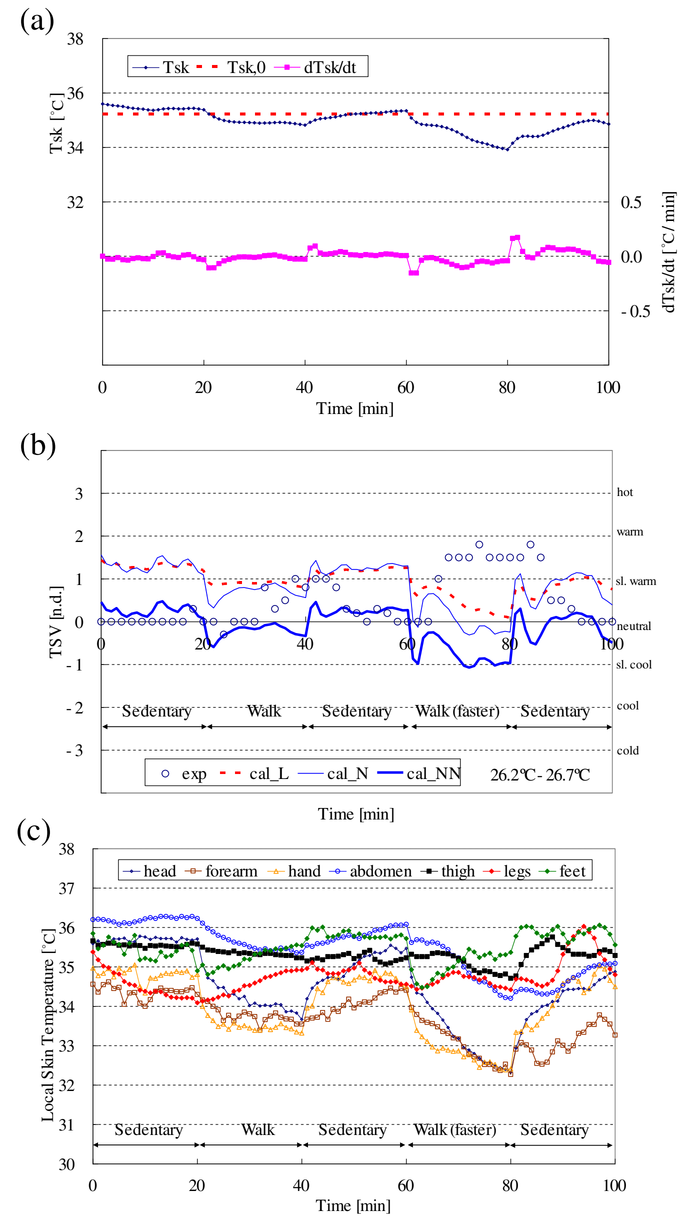

Fig. 15. (a) Mean skin temperature and its time differential (experimental) and (b) thermal sensation vote (experimental and calculated) for Subject Q, Experiment 3 (L: linear equation, N: nonlinear equation, NN: nonlinear equation when using normalized skin temperature), and (c) local skin temperatures (experimental).

steady state has a linear relationship with the mean skin temperature. The results presented by these authors correspond with the results obtained in our study.

4.4. The applicable range of the equation

Through the experiments for sedentary subjects in the artificial climate chambers (Experiment 1), it was shown that the proposed equation sufficiently predicts the TSV in a homogeneous thermal environment in the non-steady state. This finding was validated through the field experiments in which the subjects were exposed to various thermal environments, including walking processes in outdoor spaces (Experiment 2). Overall, the error in TSV prediction was sufficiently small in Experiment 2, although it grew larger with increasing difference in the behavior of the local skin temperatures.

In Experiment 3, the situation in which the error in prediction becomes large was the focus. As shown in Figs. 14 and 15, when walking, the skin temperatures of the upper half of the body decreased due to convective cooling, while those of the lower half of the body increased due to heat production by the subject's muscles. The proposed equation is based on the mean skin temperature and its time differential; therefore the precision of the prediction is reduced when the behavior differs significantly between the skin segments to the extent that the skin temperatures of some segments change inversely with respect to those of the other segments. During walking, as can be observed in the first walking process in Experiment 2, the changes in the local skin temperatures are approximately synchronous with the abrupt change in the ambient thermal environment, and the prediction error is small. Thus, the proposed equation for the prediction of the thermal

Table 7
Regression coefficients and correlation coefficient (“N” or nonlinear equation without normalization of skin temperature).

Regression coefficient							Correlation coefficient	Number of data
a_1	a_2	a_3	a_4	a_5	a_6	a_7		
−6.116	35.861	39.484	2.064	3.686	−0.038	0.169	0.839	6082

Table 8
Regression coefficients and correlation coefficient (“L” or linear equation without normalization of skin temperature).

Regression coefficient			Correlation coefficient	Number of data
a_1	a_2	a_3		
−25.119	0.746	2.255	0.799	6082

sensation in the non-steady state is applicable to many situations, unless a significant difference in the skin temperature or its time differential between the body segments exists.

The interviews performed on the subjects after the completion of Experiment 3 revealed that the subjects had difficulty in describing the thermal sensation over their entire bodies while walking in a constant air temperature. For example, they described cold hands but warm feet. In this case, the subjects described the whole-body sensation by synthesizing the different sensations between segments, and this is sometimes a delicate judge for a subject. The proposed equation should be applied carefully in situations that involve non-homogeneous conditions with respect to airflow, clothing, muscle heat production, etc. The results obtained in this paper suggest the possibility of developing the quantitative logical model to integrate the different signals from each segment of the skin (i.e., some segments are hot, while others are cold) for the case in which a significant difference in skin temperatures coexists between body segments, using the skin temperature and time differential.

4.5. The necessity of considering core temperature to predict thermal sensation in the non-steady state

This study is an attempt to describe the thermal sensation in a non-steady state using only skin temperature and its time differential. The influence of the core temperature is neglected in the proposed model. For the homogeneous thermal environment under the sedentary activities conditions, the core temperature can be neglected because the proposed equation explains well the numerical value and the trends of thermal sensation votes in non-steady states caused by the stepwise ambient temperature change. For some walking processes, it is not easy to predict with sufficient precision by using only the averaged skin temperature from the body surface. However, this does not mean that it is necessary to use the core temperature as an index to explain thermal sensation. From Figs. 14(c) and 15(c), the trend in thermal sensation seems to be due to either one of the local skin temperatures (increasing or decreasing group). This suggests the possibility of explaining thermal sensation using only skin temperature and its time differential.

In this study, the core temperature was not studied as a parameter for explaining the thermal sensation; at this moment, it is not possible to completely deny the contribution of core temperature to thermal sensation in the non-steady state. However, it was shown that the equation as a function of mean skin temperature and its time differential can be used for many situations that appear in the everyday scenes encountered in human living. As pointed out in the Introduction, the convenience obtained when the core temperature is not considered is significant. If the technique of sensing skin temperature is conducted in a simple manner (for example, without establishing contact with the human subject), the possibility of applying the equation proposed in this paper might be extended.

5. Conclusion

An equation for predicting whole-body thermal sensation in the non-steady state based on mean skin temperature (Hardy and DuBois's 7-point method) and its time differential was proposed based on nonlinear regression analysis using the data obtained from subject experiments on various types of thermally transient exposure in a sedentary condition. By showing the agreement between the thermal sensation votes from the experimental data and the data calculated by the proposed model, it was revealed that the proposed equation, which is an additive of Lorentzian cumulative functions, successfully predicted thermal sensation in the non-steady state for sedentary conditions in a thermally homogeneous environment. The validity of the proposed equation for the condition was also shown through the field experiments. Additionally, the applicable range of the proposed equation was studied through field experiments, which included not only sedentary conditions in a thermally homogeneous environment but also walking processes and situations in which the subjects were exposed to inhomogeneous environments such as non-air-conditioned rooms and outdoor spaces. The proposed equation was shown to predict the trend of thermal sensation vote for not only sedentary conditions in thermally homogeneous environments but also light exercise activities in inhomogeneous environments, unless the direction of the change (i.e., increase or decrease) in the local skin temperatures between body segments did not differ significantly. In this study, as an example of significant difference, the walking process in a constant-temperature environment was studied. The skin temperatures of the lower half of the body increase by the heat generation of muscle activity, while those on the upper half of the body decrease as a result of convective heat loss. To quantify the applicable limit and to expand the applicable range of the proposed equation, it is necessary to develop a modified model that includes weighted skin temperatures from various body segments, specifically when their behaviors of these segments differ significantly. The experimental data of skin temperature distribution obtained in this paper suggest the possibility of developing such a model, which can be adapted for inhomogeneous skin temperature behaviors.

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Nomenclature

a	Regression coefficient
t	Time [min]
T_{sk}	Mean skin temperature [°C]
$T_{sk,n}$	Normalized mean skin temperature [°C]
$T_{sk,0}$	Mean skin temperature in the thermally neutral and steady states for each experiment [°C]
TSV	Thermal sensation vote [n.d.]

Notes (Mean skin temperature based on Hardy & DuBois's 7-point method) $T_{sk} = 0.07 \times T_{sk,head} + 0.14 \times T_{sk,forearm} + 0.05 \times T_{sk,hand} + 0.35 \times T_{sk,abdomen} + 0.19 \times T_{sk,thigh} + 0.13 \times T_{sk,legs} + 0.07 \times T_{sk,feet}$

References

[1] Fanger PO. Thermal comfort. Danish Technical Press; 1970.

[2] Gagge AP, Stolwijk JAJ, Hardy JD. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. Environmental Research 1967;1:1–20.

[3] Gagge AP, Stolwijk JAJ, Nishi Y. The prediction of thermal comfort when thermal equilibrium is maintained by sweating. ASHRAE Transactions 1969;75(2):108–25.

[4] Gonzalez RR, Gagge AP. Magnitude estimates of thermal discomfort during transients of humidity and operative temperature and their relation to the new ASHRAE effective temperature (ET*). ASHRAE Transactions 1973;79:88–96.

[5] Nevins RG, Gonzalez RR, Nishi Y, Gagge AP. Effect of changes in ambient temperature and level of humidity on comfort and thermal sensations. ASHRAE Transactions 1975;81(2):169–83.

[6] Rohles FH, Hayter RB, Milliken G. Effective temperature (ET*) as a predicitor of thermal comfort. ASHRAE Transactions 1975;81(2):148–56.

[7] Kuno S, Ohno H, Nakahara N. A two-dimensional model expressing thermal sensation in transitional conditions. ASHRAE Transactions 1987;93(2):396–406.

[8] Goto T, Toftum J, de Dear R, Fanger PO. Thermal sensation and thermophysiological responses to metabolic step-changes. International Journal of Biometeorology 2006;50:323–32.

[9] Munir A, Takada S, Matsushita T. Reevaluation of Stolwijk's 25-node human thermal model under thermal transient conditions: prediction of skin temperature in low activity conditions. Building and Environment 2009;44(9):1777–87.

[10] Takada S, Sakiyama T, Matsushita T. Validity of the two-node model for predicting steady state skin temperature. Building and Environment 2011;46(3):597–604.

[11] Mori I, Hokoi S, Takada S, et al. Experimental study on thermal sensation index in thermal transient. Journal of Architecture, Planning and Environmental Engineering (Transactions of AIJ) 2003;563:9–15 [in Japanese with English abstract].

[12] Fiala D, Lomas KJ, Stohrer M. First principles modeling of thermal sensation responses in steady-state and transient conditions. ASHRAE Transactions 2003:179–87.

[13] Zhang H, Arens E, Huizenga C. Thermal sensation and comfort models for non-uniform and transient environments: part I: local sensation of individual body parts. Building and Environment 2010;45:380–8.

[14] Zhang H, Arens E, Huizenga C. Thermal sensation and comfort models for non-uniform and transient environments: part II: local comfort of individual body parts. Building and Environment 2010;45:389–98.

[15] Zhang H, Arens E, Huizenga C. Thermal sensation and comfort models for non-uniform and transient environments: part III: whole-body sensation and comfort. Building and Environment 2010;45:399–410.

[16] Frank SM, Raja SN, Bulcao CF, Goldstein DS. Relative contribution of core and cutaneous temperatures to thermal comfort and autonomic responses in humans. Journal of Applied Physiology 1999;86(5):1588–93.

[17] Mower GD. Perceived intensity of peripheral thermal stimuli is independent of internal body temperature. Journal of Comparative and Physiological Psychology 1976;90(12):1152–5.

[18] Hensel H. Thermoreception and temperature regulation. In Monographs of physiological society, vol. 38. Academic Press; 1981. p. 33–5.

[19] Ring JW, de Dear R. Temperature transients: a model for heat diffusion through the skin, thermoreceptor response and thermal sensation. Indoor Air 1991;4:448–56.

[20] Ring JW, de Dear R, Melikov A. Human thermal sensation: frequency response to sinusoidal stimuli at the surface of the skin. Energy and Buildings 1993;20:159–65.

[21] Hardy JD, Stolwijk JAJ. Partitional calorimetric studies of man during exposures to thermal transients. Journal of Applied Physiology 1966;21:1799–806.

[22] Takada S, Kobayashi H, Matsushita T. Thermal model of human body fitted with individual characteristics of body temperature regulation. Building and Environment 2009;44(3):463–70.

[23] Mitchell D, Wyndham CH. Comparison of weighting formulas for calculation mean skin temperature. Journal of Applied Physiology 1969;26(5):616–22.

[24] Ogawa S, et al. Experimental study on the optimum thermal condition. The Bulletin of the High Institute of Public Health 1974;23(2):72–87 [in Japanese with English abstract].